Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum

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[1] Geophysical data show that during the last glaciation the West Antarctic Ice Sheet (WAIS) drained to the continental shelf edge of the Bellingshausen Sea through a cross-shelf bathymetric trough (Belgica Trough) as a grounded, fast flowing, ice stream. The drainage basin feeding this ice stream probably encompassed southwestern Palmer Land, parts of southern Alexander Island, and the Bryan Coast of Ellsworth Land, with an area exceeding 200,000 km^2. On the inner continental shelf, streamlined bedrock and drumlins mapped by swath bathymetry show that the ice stream was fed by convergent ice flow draining from Eltanin Bay and bays to the east, as well as by ice draining the southern part of the Antarctic Peninsula Ice Sheet through the Ronne Entrance. The presence of a paleoice stream in Belgica Trough is indicated by megascale glacial lineations formed in soft till and a trough mouth fan on the continental margin. Grounding zone wedges on the inner and midshelf record ice marginal stillstands during deglaciation and imply a staggered pattern of ice sheet retreat. These new data indicate an extensive WAIS at the Last Glacial Maximum (LGM) on the Bellingshausen Sea continental margin, which advanced to the shelf edge. In conjunction with ice sheet reconstructions from the Antarctic Peninsula and Pine Island Bay, this implies a regionally extensive ice sheet configuration during the LGM along the Antarctic Peninsula, Bellingshausen Sea, and Amundsen Sea margins, with fast flowing ice streams draining the WAIS and Antarctic Peninsula Ice Sheet to the continental shelf edge.

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1. Introduction

[2] Geophysical investigations of submarine landforms and sediments are fundamental to the accurate reconstruction of the dimensions and dynamics of Quaternary ice sheets. This is illustrated by the case of the Antarctic Ice Sheet during the Last Glacial Maximum (LGM) when the ice sheet expanded onto the continental shelf and, in some localities, reached the shelf edge [*Pudsey et al.*, 1994; *Larter and Vanneste*, 1995; *Ó Cofaigh et al.*, 2002, 2005; *Lowe and Anderson*, 2002; *Anderson et al.*, 2002; *Dowdeswell et al.*, 2004; *Evans et al.*, 2005]. The landforms and sediment recording this ice sheet advance across the continental shelf are now exposed at the seafloor following ice sheet retreat and are only accessible using marine geophysical and geological techniques.

[3] Current interest in the stability of the marine-based West Antarctic Ice Sheet (WAIS) centers on the possibility of its total or partial collapse, and the corresponding effect of such a collapse on eustatic sea level [*Bindschadler*, 1998]. Central to this question is the configuration and extent of WAIS at the LGM, as well as the style and rate of its subsequent retreat. These are fundamental to any attempts to model the contribution of WAIS to sea level rise since the LGM. Estimates of the magnitude of such a contribution are variable and depend upon the ice sheet reconstruction used in the model, which, in turn, depends on accurate geological inputs [cf. *Nakada and Lambeck*, 1998; *Huybrechts*, 1990, 2002; *Tushingham and Peltier*, 1991; *Nakada et al.*, 2000]. Although the configuration and dynamics of the WAIS through the last glacial-deglacial cycle are reasonably well known for several areas around Antarctica such as the Ross Sea [*Shipp et al.*, 1999; *Domack et al.*, 1999; *Licht et al.*, 1999; *Wellner et al.*, 2001] and the Antarctic Peninsula margin [*Pope and Anderson*, 1992; *Pudsey et al.*, 1994; *Larter and Vanneste*, 1995; *Canals et al.*, 2000; *Ó Cofaigh et al.*, 2005; *Evans et al.*, 2005], there still remain large gaps in key areas. One such area is the continental margin of the Bellingshausen Sea (Figure 1).

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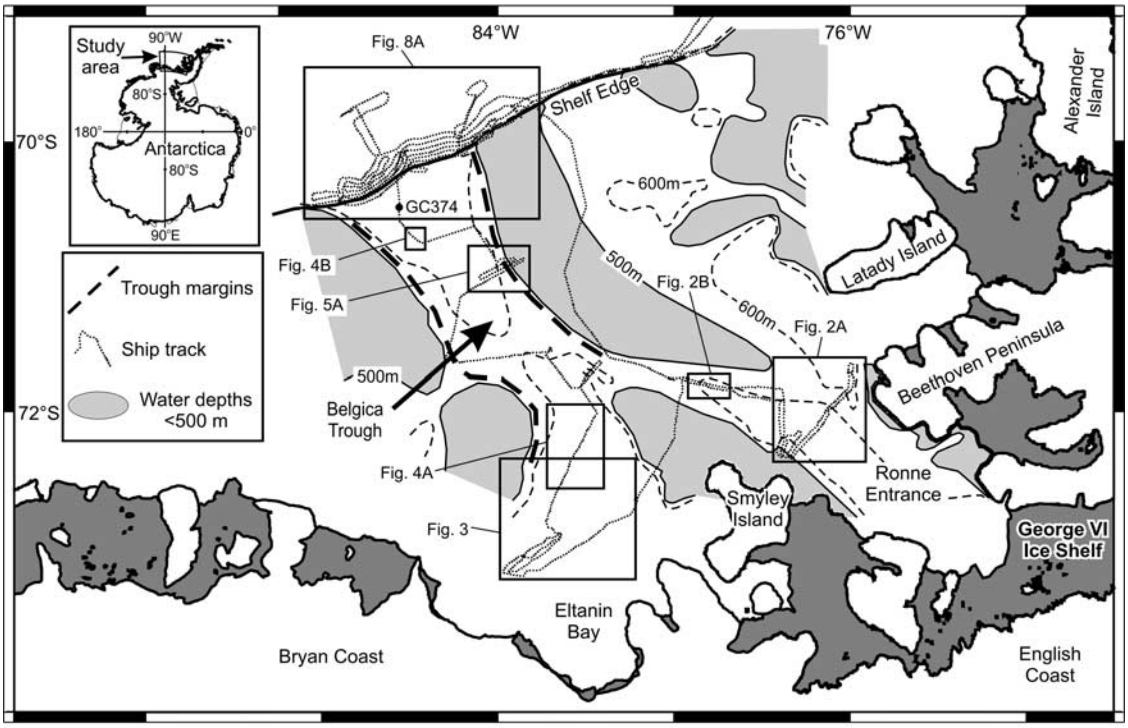

Figure 1. Location map of the study area showing ship track, place names referred to in text, margins of Belgica Trough, and locations of subsequent figures. Map projection is Mercator. The 500 m (thin solid lines) and 600 m (thin dashed lines) bathymetric contours on the shelf are based on multibeam echo sounder data from cruise JR104 of the RRS *James Clark Ross*, cruises of the R/V *Nathaniel B Palmer* and R/V *Polarstern*, and a collation of single beam soundings provided by the UK Hydrographic Office. Charted water depths of less than 500 m are indicated by the grey fill.

[4] Until recently there have been only limited data available from the continental shelf and slope of the southern Bellingshausen Sea, and ice sheet extent at the LGM in this region was largely unknown [*Bentley and Anderson*, 1998; *Bentley*, 1999]. More recently, however, marine geological and geophysical investigations from Eltanin Bay on the inner continental shelf, identified a large bathymetric trough as well as a variety of streamlined subglacial bed forms including erosional grooves, drumlins and megascale glacial lineations (MSGL) [*Wellner et al.*, 2001]. The new data we present in this paper show that the trough continues to the shelf edge, and it is informally named here as "Belgica Trough". *Wellner et al.* [2001] inferred that the former grounding line of the WAIS during the LGM was on the midshelf, beyond their area of data coverage. Seismic profiles had already revealed that the outer continental shelf and upper slope at the mouth of the trough in this region comprise a series of prograded sequences that record a seaward migration of the shelf edge by more than 35 km [*Cunningham et al.*, 1994; *Nitsche et al.*, 1997, 2000]. Collectively, these observations suggested that a grounded WAIS advanced into Eltanin Bay and to the shelf edge in this region at some time in the past. However, the timing (LGM or pre-LGM?) of this advance was unknown and direct glacial geomorphological evidence for a grounded ice sheet on the outer shelf has not been observed to date.

[5] In this paper we address three questions. (1) What was the extent and configuration of grounded ice in the southern Bellingshausen Sea at the LGM; in particular, did an expanded WAIS reach the edge of the continental shelf? (2) What is the landform/sediment record of ice sheet advance and retreat across the shelf and what does this record tell us about conditions at the former ice sheet bed? (3) What was the style of ice sheet retreat during deglaciation; was retreat rapid or staggered? These questions are important because depending on the size of the paleoice sheet drainage basin, Belgica Trough could have been one of the largest pathways for outflow from the WAIS at the LGM [*Larter et al.*, 2004]. However, an absence of multibeam swath bathymetric data from the outer continental shelf, as well as from the Ronne Entrance and an associated paucity of acoustic subbottom profiler data, has prevented such a regional reconstruction of paleoice sheet extent and configuration. New geophysical data presented in this paper allow such a reconstruction to be made for the continental margin of the Bellingshausen Sea for the first time.

2. Data Acquisition and Methods

[6] Geophysical and geological data were acquired on the continental shelf and slope of the Bellingshausen Sea during cruise JR104 of RRS *James Clark Ross* in January–February 2004. Geophysical data were collected using a hull-mounted Kongsberg-Simrad EM120 multibeam swath bathymetry system and a TOPAS subbottom profiler. The EM120 system emits 191 beams, each with dimensions of 1° by 1° and frequencies in the range of 11.75–12.75 kHz. The swath data allowed detailed mapping of the shape of the seafloor. Profiles of the sound velocity structure of the water column were

collected regularly during the cruise using expendable bathythermographs (XBTs). The sound velocity profiles were input to the swath bathymetry acquisition system in order to correct for the varying velocity and refraction of sound waves through the water column. Data processing was carried out using Kongsberg-Simrad NEPTUNE software and involved removal of anomalous data points and application of the sound-velocity profiles derived from the XBT data. The EM120 data were gridded at cell sizes of 50–100 m depending on water depth and thus survey size. Vertical and horizontal uncertainties are about 1 m and 5 m, respectively.

[7] The TOPAS parametric acoustic profiler produces a narrow (5°) beam with user-specified secondary frequencies in the range of 0.5 to 5 kHz. Generally, on the continental shelf in water depths of less than 1000 m, the TOPAS system was operated with a transmitted signal consisting of just one or two cycles of a fixed secondary frequency of 2.8 kHz. Vertical resolution is better than 1 m. The maximum depth of sediment penetration by TOPAS is variable and depends on the nature of the sediments. In general, fine grained sediments can be imaged by TOPAS to greater depths (>150 m penetration can be achieved) than coarser grained and poorly sorted deposits (typically <40 m). In this study TOPAS generally penetrated sediments to depths of between 2 and ~25 m. Navigation data were acquired using differential GPS. The area of geophysical data acquisition is shown in Figure 1.

[8] Core GC374 was recovered with a gravity corer at 70°30.0′S and 86°14.2′W from a water depth of 650 m. The core recovery was 1.96 m. Magnetic susceptibility and wet bulk density were measured on the whole core at the British Ocean Sediment Core Research Facility (National Oceanography Centre, Southampton, UK), using a GEOTEK multisensor core logger. Shear strength was measured with a torvane on the split core. The water content was determined on discrete samples.

3. Geophysical Data

3.1. Ronne Entrance

[9] Swath bathymetric data show glacial geomorphological evidence for two flow sets that record ice flow out of the Ronne Entrance: a WNW oriented set of bed forms recording flow into the head of Belgica Trough and another NNW oriented set recording flow into a probable cross-shelf bathymetric trough west of Beethoven Peninsula (Figures 1 and 2a). The NNW flow set comprises well-developed, attenuated drumlins and megascale glacial lineations that are up to 12–13 km long, 100–600 m wide, ≤10 m high, with elongation ratios of between 15:1 and 51:1, and which occur in water depths of 600–700 m (Figure 2c). Some drumlins have well-developed, crescent-shaped, overdeepenings around their upstream ends. The set of WNW oriented bed forms occurs in water depths of less than ~550 m where the trough shallows upward to the side of Smyley Island (Figure 2a). Bed forms are less well developed than the NNW flow set and are typically shorter; usually about 3 km in length, exceptionally reaching 7 km.

[10] Streamlined bed forms are generally absent from the intervening area of the trough between these two flow sets (Figure 2a). Water depths in this intervening area are 600–700 m. TOPAS subbottom profiler records from the mouth of the Ronne Entrance commonly show a rough seafloor with little sediment. However, at about 71°55′S and 76°10′W an acoustically transparent unit up to 12 m thick, with occasional faint internal reflectors, overlies a prominent, typically smooth subbottom reflector (Figure 2e).

[11] Faint lineations oriented WNW do occur, however, about 25 km further downflow in water depths of 600–700 m, where they record ice flow from the Ronne Entrance toward the head of Belgica Trough (Figure 2a). TOPAS data show that, internally, the lineations are composed of acoustically transparent sediment and form isolated ridges sitting on the seafloor (Figure 2d). Megascale glacial lineations (MSGL) recording the continuation of this WNW flow were imaged at 71°48′S and 79°15′W (Figures 1 and 2b). These MSGL are up to 10 km in length, have elongation ratios up to 46:1, and occur in water depths of ~570–620 m. TOPAS data from this area show that the lineations are formed in a patchy unit of acoustically transparent sediment that exceptionally reaches a maximum thickness of about 14 m and overlies a subbottom reflector.

3.2. Eltanin Bay

[12] Eltanin Bay is located west of the Ronne Entrance and Smyley Island (Figure 1). Water depths in the bay range from about 500 to 1200 m. Streamlined subglacial bed forms were imaged on the floor of Eltanin Bay using multibeam swath bathymetry and these new data build on previous multibeam surveys [*Wellner et al.*, 2001]. Crudely streamlined forms and drumlins, some with crescentic overdeepenings around their stoss ends, occur in the inner bay between 73°08′S and about 72°40s (Figure 3). Bed form lengths range from 1 to 10 km. The rough appearance of the crudely streamlined bed forms on the swath bathymetric records, their similarly rough and irregular appearance on TOPAS records and associated lack of acoustic penetration, imply that they are formed predominantly in bedrock (i.e., crystalline rocks or lithified sediments) and/or that unconsolidated sediment cover is thin and localized.

[13] The orientation of the bed forms indicates that flow from Eltanin Bay was convergent with ice flow emanating from bays west of Smyley Island (as recorded by streamlined bedrock – Figure 3), and this convergent flow focused northward into Belgica Trough. Drumlins evolve into MSGL in the trough north of about 72°35′S (Figure 4a). In Pine Island Bay, *Lowe and Anderson* [2002] observed that the transition from drumlins to MSGL occurred at the exact position where a seismic reflection profile revealed the landward edge of a wedge of unconsolidated sediment. The substrate may exert a similar control here, but no seismic profiles have yet been collected in Eltanin Bay. The orientation of the bed forms indicates that ice flow was initially northward out of Eltanin Bay to about 72°25′S, where it then swung around to a more NW orientation as recorded by MSGL in Belgica Trough.

3.3. Belgica Trough

[14] MSGL occur in water depths of 560–700 m on the floor of Belgica Trough (Figures 4 and 5). In dimensions, the MSGL are up to 9 km in length and have elongation ratios of up to 37:1 (their maximum dimensions are con-

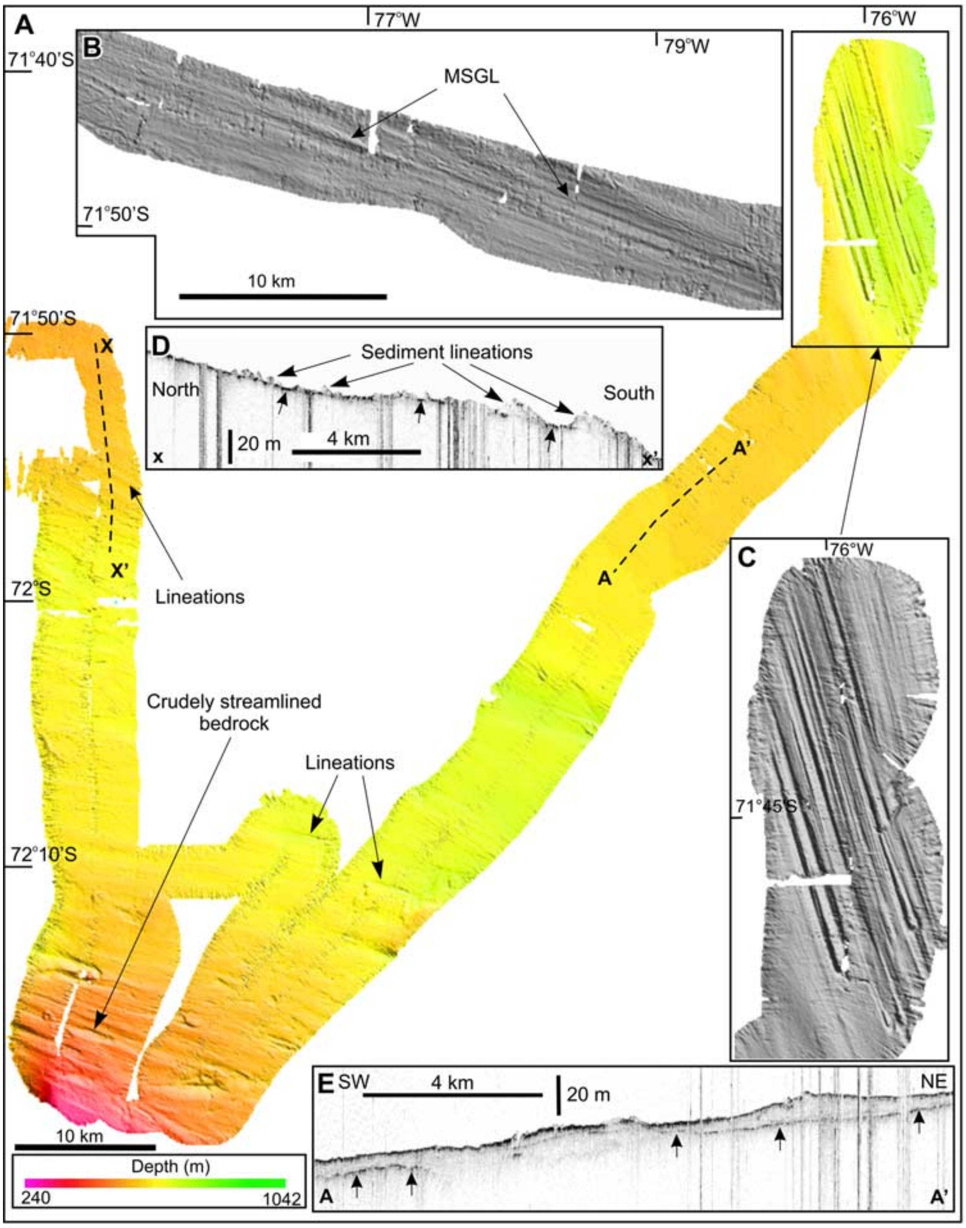

Figure 2. Geophysical records of paleoice sheet flow from the Ronne Entrance. Locations of plots are shown in Figure 1. (a) EM120 (12 kHz) multibeam swath bathymetry, color draped, shaded relief image of the seafloor at the mouth of the Ronne Entrance. Direction of illumination of this and subsequent shaded relief images is from the northeast. Note the two flow sets of streamlined subglacial bed forms recording WNW oriented flow toward Belgica Trough and NNW orientated flow west of Beethoven Peninsula. The crudely streamlined WNW set is formed predominantly in bedrock. Grid cell size is 50 m × 50 m. (b) Shaded relief swath bathymetry image of megascale glacial lineations (MSGL) formed in sediment in water depths of 570–620 m. The MSGL record WNW ice flow from the Ronne Entrance toward the head of Belgica Trough. Grid cell size is 50 m × 50 m. (c) Blow-up of attenuated drumlins and lineations recording NNW oriented ice flow from the Ronne Entrance toward the edge of the continental shelf. Location of image shown in Figure 2a. Grid cell size is 50 m × 50 m. (d) TOPAS subbottom profiler record through lineations recording WNW orientated ice flow from the Ronne Entrance. Location of profile X-X′ is shown in Figure 2a. The lineations form individual ridges that are composed of acoustically transparent sediment and sit above a prominent reflector (arrowed) that is exposed at the seafloor in places between the ridges. (e) TOPAS subbottom profiler record from the Ronne Entrance showing acoustically transparent sediment unit sitting above a prominent basal reflector (arrowed). Location of the profile A-A′ is shown in Figure 2a. Note that map projection in Figures 2a, 2b, and 2c is UTM.

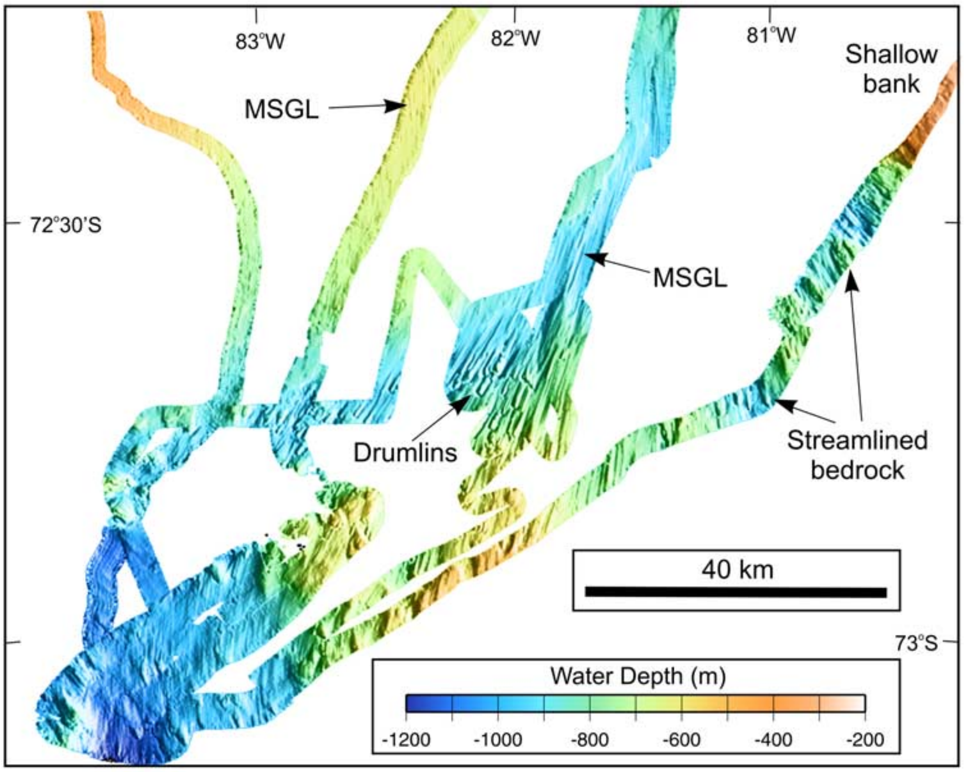

Figure 3. Multibeam swath bathymetry (color draped, shaded relief) image of streamlined subglacial bed forms on the floor of Eltanin Bay. Location is shown in Figure 1. The orientation of the streamlined bed forms indicates flow convergence into the head of Belgica Trough. Grid cell size is 100 m × 100 m. The multibeam data are a combination of EM120 (12 kHz, present study), SeaBeam 2100 (12 kHz) data from cruise 9902 of the R/V *Nathaniel B Palmer* (Lamont-Doherty Earth Observatory Marine Geoscience Data Management System Antarctic Multibeam Synthesis) and Hydrosweep (15 kHz) data from the R/V *Polarstern* cruise ANT-XI/3 (Alfred Wegener Institute). Map projection is UTM.

strained by the extent of our swath coverage). TOPAS data from the MSGL show that they are developed in the upper part of an acoustically transparent sediment unit that is up to about 17 m thick and which is underlain by a prominent subbottom reflector (Figure 5b). Typically, this unit appears to be homogeneous internally. However, in some locations internal reflectors are present and the unit is overlain by 3–4 m of sediment characterized by a more prolonged acoustic return. The MSGL record former ice flow along the trough toward the edge of the continental shelf.

[15] Core GC374 was recovered from the acoustically transparent unit in outer Belgica Trough (Figure 1). There are four units in the core (Figure 6). The lowermost 161 cm comprises a massive, homogenous, grey diamict. This unit is predominantly dark grey (N4/) but undergoes a sharp color change to 2.5Y 4/2 4 cm from its top. The diamict is overlain gradationally by 21 cm of greyish brown (2.5Y 4/2), mottled terrigenous sandy mud, the lowermost 4 cm of which comprises a gravely layer. The sandy mud is overlain by 8 cm of gravel-bearing, bioturbated muddy sand (5Y 4/2), and the core is capped by 4 cm of greyish brown (10YR 4/2), bioturbated foraminiferal ooze. The shear strength of the foraminiferal ooze, muddy sand and sandy mud is less than 12 kPa, whereas shear strength increases to values >20 kPa within the diamict. Wet bulk density exhibits a significant downcore increase from the foraminiferal ooze to the upper part of the sandy mud unit but only a slight increase in the underlying sediments. The water content decreases downcore, reflecting an inverse correlation with wet bulk density. Some of the major peaks in wet bulk density and magnetic susceptibility are related to the presence of pebbles and cobbles that were observed in the split core. The diamict below c. 80 cm core depth is interpreted as a subglacial till deposited by a grounded ice stream during the last glacial period based on its massive structure, high shear strength and low water content [cf. *Domack et al.*, 1999; *Evans and Pudsey*, 2002; *Ó Cofaigh et al.*, 2005; *Hillenbrand et al.*, 2005]. The upper part of the massive diamict facies (shear strength <12 kPa) and the overlying sandy mud, which underlie the foraminiferal ooze, were probably deposited during deglaciation, and record the initial transition from grounded to floating ice. The foraminiferal ooze is interpreted as a product of glaciomarine sedimentation under seasonally open marine conditions during the present interglacial.

[16] Swath bathymetric data from outer Belgica Trough at 71°S 84°W show MSGL in water depths of 560–620 m. The lineations are terminated downflow by irregularly shaped furrows which are interpreted as iceberg scours (Figure 5a). The switch between MSGL and the iceberg

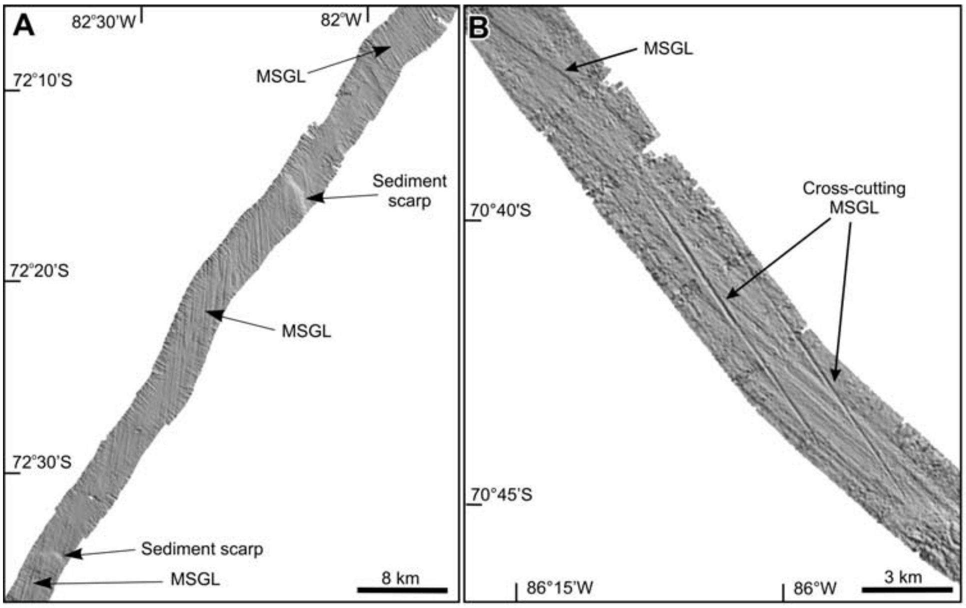

Figure 4. EM120 multibeam swath bathymetry images of megascale glacial lineations (MSGL) recording flow of grounded ice along Belgica Trough. Locations of plots are shown in Figure 1. (a) MSGL in water depths of about 700 m from the midshelf trough. Note the sediment scarps (labeled). The northern scarp forms the NE end of the TOPAS transect "X-X′" shown in Figure 7b and is interpreted as the edge of a grounding zone wedge (see text). The sediment scarps interrupt the MSGL. (b) Crosscutting MSGL in 660–670 m water depth from the outer shelf trough. Grid cell size is 40 m × 40 m. Map projection in both Figures 4a and 4b is UTM.

scours occurs over a distance of about 1–3 km. Iceberg scours are also present outside of the trough on the shallower banks in water depths of less than 460 m (Figure 5a). MSGL were mapped northward to within 40 km of the shelf edge at 70°37′S (Figure 4b). North of this location, the seabed is iceberg scoured and the quality of multibeam data obtained on the outer shelf was poor due to extensive sea ice. TOPAS records show that the MSGL are developed in the upper part of an acoustically transparent sediment unit that can be 30–40 m thick and overlies a strong subbottom reflector.

[17] In several locations in the inner and middle parts of Belgica Trough, TOPAS data show sediment accumulations with steeply dipping, subbottom reflectors, which are truncated by a flat to gently dipping reflector that is, in turn, overlain by an acoustically transparent sediment unit (Figure 7). This acoustic sequence bears similarities to the foresets and top sets of Gilbert-type deltas, and it is similar to the till deltas or grounding zone wedges (GZWs) described previously from the Antarctic continental shelf [cf. *Alley et al.*, 1989; *Larter and Vanneste*, 1995; *Vanneste and Larter*, 1995; *Anderson*, 1997, 1999; *Bart and Anderson*, 1997]. These features are therefore interpreted as GZWs.

[18] Figure 7b shows a GZW between 72°15′S 82°10′W and 72°32′S 82°38′W. In dimensions it is over 20 m thick and about 40 km long; although it is possible that it is a composite feature composed of more than one back-stepping GZW. It terminates at a prominent scarp 25–30 m high at its downflow end (Figure 7b). The swath bathymetric data suggest that this scarp may be slightly oblique to former ice flow. MSGL are incised into the surface of the GZW but do not continue across the scarp, and MSGL also initiate immediately downflow of the scarp (Figure 4a). The scarp therefore interrupts the MSGL. A second smaller scarp occurs at 72°33′S 82°39′W. This scarp is about 5–6 m in height. MSGL are incised into its upper surface and also occur immediately downflow of the scarp. However, once again it appears that the scarp interrupts the MSGL and the bed forms do not continue across it. The surface of the other GZWs identified on TOPAS records are either iceberg scoured or severe pack ice resulted in the swath data being of poor quality.

3.4. Continental Slope

[19] Belgica Trough is about 150 km wide where it reaches the edge of the continental shelf (Figure 8). The shelf break occurs in water depths of 600–670 m, and iceberg plough marks are present on the seafloor at, and inshore of this. Bathymetric contours on the upper slope are fairly straight in profile down to about 1200 m (Figure 8a). Below this depth, however, the contours exhibit a distinct bulge shape, which extends down to at least 2400 m (the limit of data coverage). The outward bulging of slope contours is limited to the area directly in front of Belgica Trough. TOPAS records from the continental slope in front of the trough mouth show the presence of acoustically transparent lenses of sediment (Figures 8b and 8c). *Nitsche et al.* [2000] describe two multichannel seismic reflection profiles which trend NW-SE and cross the continental shelf edge in the vicinity of 87°30′W in front of the trough mouth. The profiles are less than 25 km apart and show prograded depositional sequences that indicate seaward migration of

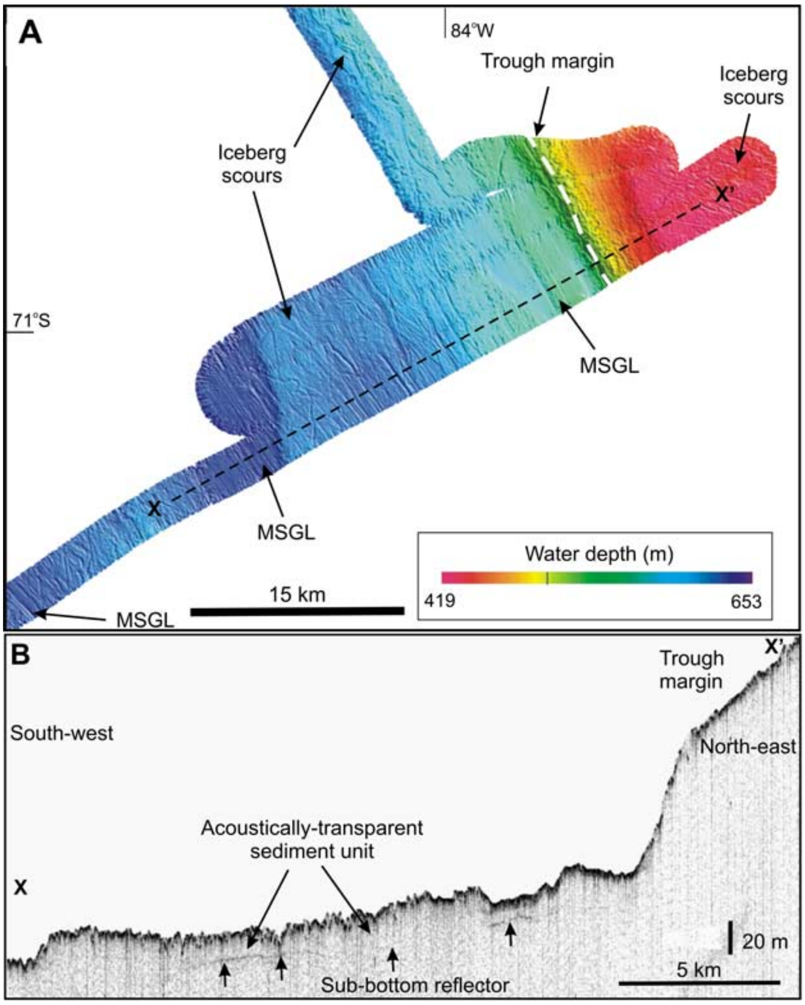

Figure 5. Geophysical records of submarine landforms and shallow acoustic stratigraphy from outer Belgica Trough. Location is shown in Figure 1. (a) EM120 multibeam (12 kHz) swath bathymetry, color draped, shaded relief image of megascale glacial lineations (MSGL) in water depths of 560–620 m. Grid cell size is 50 m × 50 m. The MSGL are obliterated downflow by iceberg plough marks. Note the presence of iceberg plough marks on the shallower bank (water depths <460 m) outside of the trough and the prominent trough margin. Map projection is UTM. (b) TOPAS subbottom profiler record of shallow acoustic stratigraphy in outer Belgica Trough. The location of the profile "X-X′" is shown in Figure 5a. Note that the MGSL are formed in an acoustically transparent sediment unit which overlies a prominent subbottom reflector (arrowed).

the shelf edge by more than 35 km during the Late Cenozoic.

4. Discussion

4.1. Ice Sheet Dynamics and Relationship to the Subglacial Substrate

[20] Ice flow through Belgica Trough is inferred to have been in the form of a fast flowing ice stream, based on several lines of evidence. (1) The bed forms are located in a cross-shelf bathymetric trough and such troughs are commonly the loci of modern and Quaternary ice streams [*Stokes and Clark*, 1999; *Vaughan et al.*, 2001, 2003; *Ó Cofaigh et al.*, 2005; *Evans et al.*, 2005]. (2) There is a convergent pattern of ice flow feeding into the head of the trough [*Stokes and Clark*, 1999]. (3) A downflow transition in subglacial bed forms within the trough, from drumlins to MSGL has been observed [cf. *Wellner et al.*, 2001; *Ó Cofaigh et al.*, 2002; *Stokes and Clark*, 2002, 2003; *Dowdeswell et al.*, 2004]. Crescentic overdeepenings around the upstream ends of several drumlins in Eltanin Bay are regarded as the product of localized meltwater erosion. Such elongate subglacial bed forms have now been observed beneath the region of accelerating ice flow in the upstream part of the modern Rutford Ice Stream in Antarctica [*King et al.*, 2003]. *King et al.* [2004] have also reported evidence of channelized subglacial meltwater flow beneath a neighboring part of this ice stream, which is consistent with our interpretation of localized meltwater erosion in Eltanin Bay. (4) MSGL are the most elongate subglacial bed form that we document and they are formed in the upper part of an acoustically transparent sediment unit in the

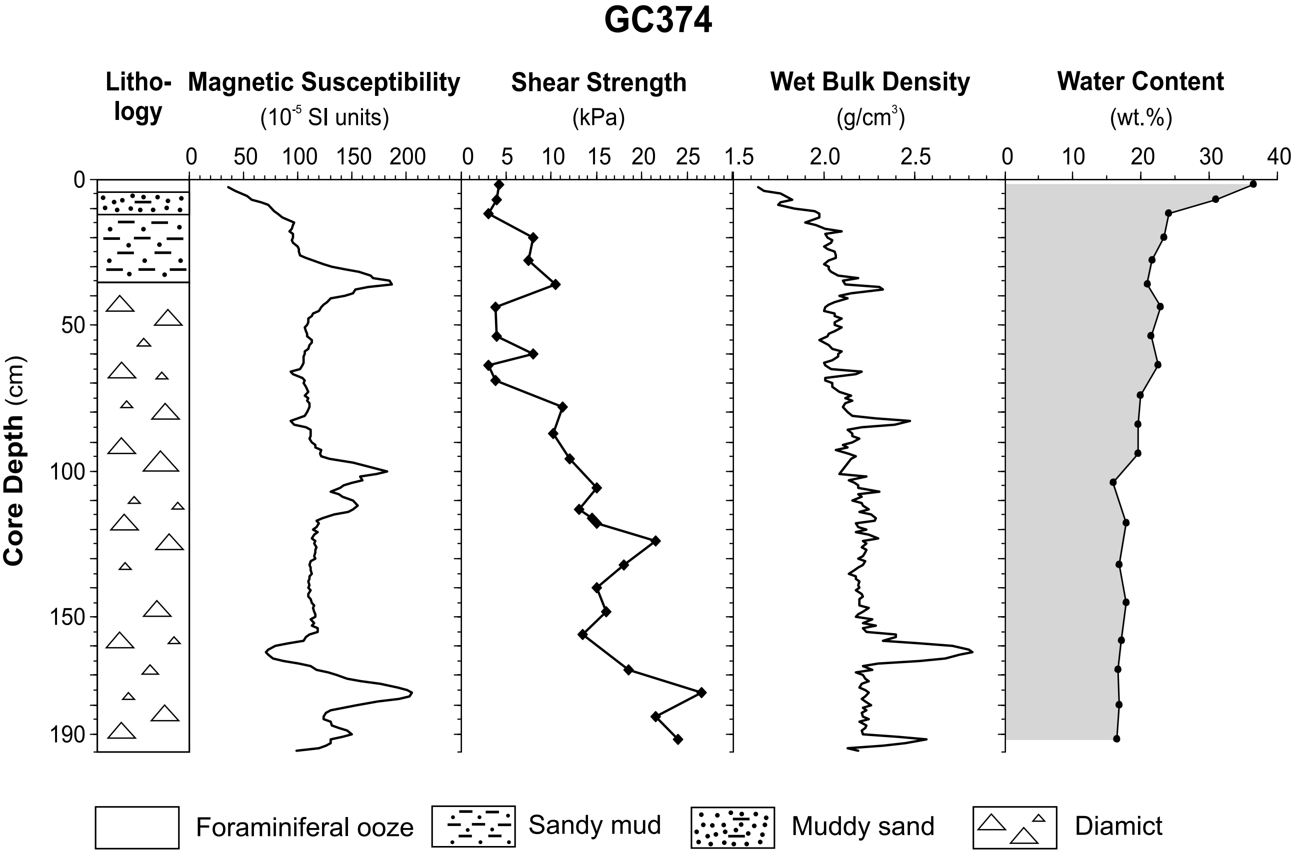

Figure 6. Lithology, physical properties, and water content of core GC374 from outer Belgica Trough. Location of core is shown in Figure 1.

trough. A similar acoustic facies has been described from other paleoice stream troughs around Antarctica, and sediment cores show that it is typically a weak, massive diamict that is the product of subglacial deformation [*Ó Cofaigh et al.*, 2002, 2005; *Dowdeswell et al.*, 2004; *Evans et al.*, 2005]. On the basis of the acoustic properties of the sediment unit within Belgica Trough, we similarly interpret it as a subglacial till that may, at least partially, be the

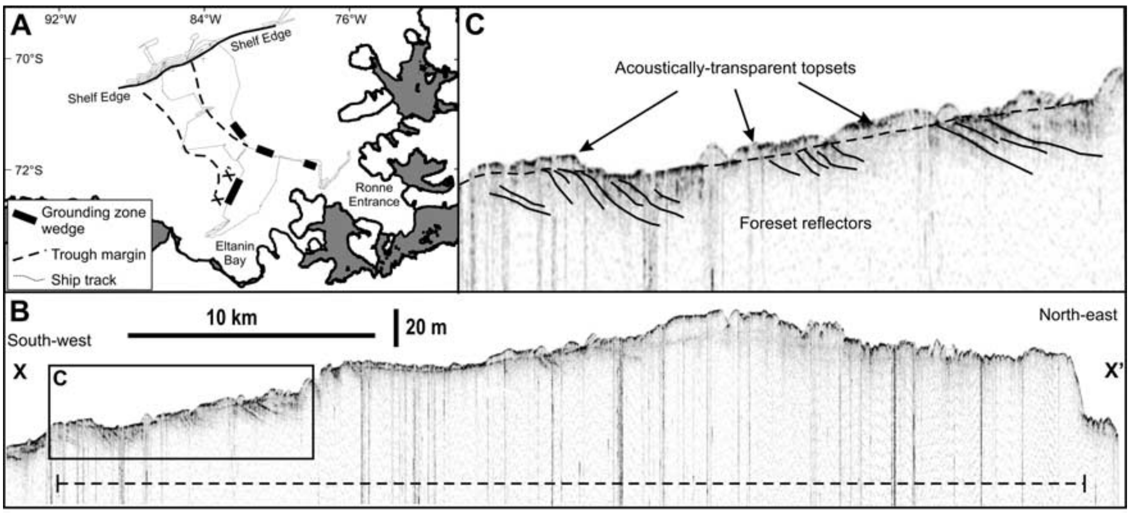

Figure 7. Grounding zone wedges (GZW) on the continental shelf of the Bellingshausen Sea. (a) Location of grounding zone wedges in the study area. (b) GZW in Belgica Trough. The dashed line shows the extent of the feature. It is possible that this is a composite landform composed of several back-stepping GZWs. Note the dipping foreset reflectors that are truncated by the gently dipping overlying reflector; the capping acoustically transparent sediment unit (top sets); the distinct wedge shape of the GZW with an abrupt and steep distal face.

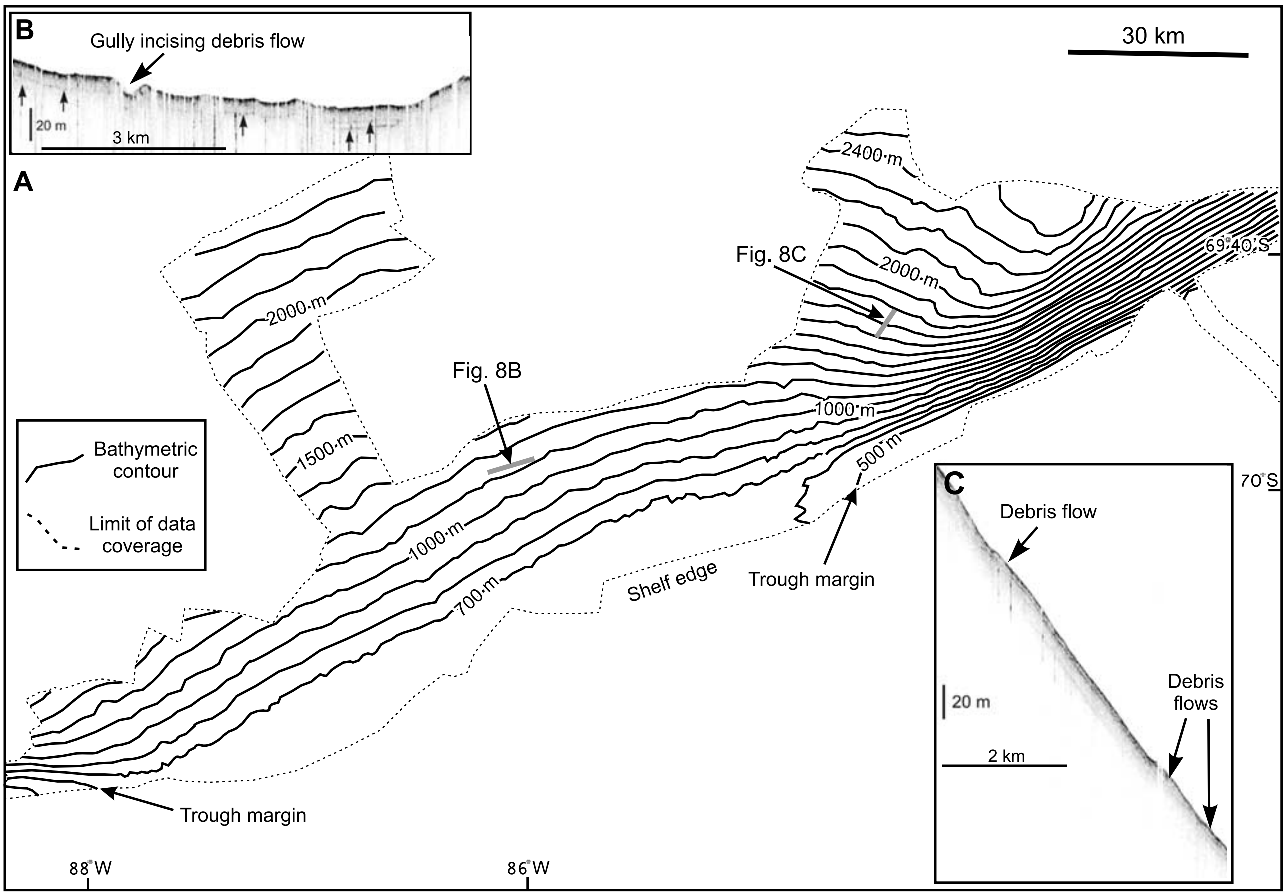

Figure 8. Bathymetric and acoustic data from the continental slope in front of Belgica Trough. (a) Bathymetry (contour interval 100 m) mapped from EM120 (12 kHz) multibeam swath bathymetry data. (b) Across-slope TOPAS subbottom profiler record of acoustically transparent sediment units interpreted as debris flows incised by a gully in water depths of 1110–1130 m. (c) Downslope TOPAS record of acoustically transparent sediment lenses interpreted as debris flows on the continental slope in front of the trough mouth in water depths of 1660–1800 m. Map projection is UTM.

product of sediment deformation. A subglacial till interpretation is also supported by core GC374 which was recovered from the acoustically transparent unit in outer Belgica Trough. At least the lower section of the structureless diamict, which exhibits high shear strength, is interpreted as a subglacial till [cf. *Wellner et al.*, 2001; *Dowdeswell et al.*, 2004; *Ó Cofaigh et al.*, 2005; *Evans et al.*, 2005]. MSGL formation is therefore associated with the presence of a soft till layer within the trough.

[21] In addition, the outward bulging bathymetric contours in front of Belgica Trough (Figure 8) and the acoustically transparent sediment lenses imaged by TOPAS on the slope are interpreted as representing a trough mouth fan composed of debris flow deposits [cf. *Laberg and Vorren*, 1995, 2000; *Taylor et al.*, 2002; *Ó Cofaigh et al.*, 2003]. In conjunction with seismic profiles from the outermost shelf and upper slope [*Cunningham et al.*, 1994; *Nitsche et al.*, 1997], these data imply that progradation of the margin occurred in front of Belgica Trough [cf. *Vorren et al.*, 1989, 1998; *Dowdeswell et al.*, 1996]. Trough mouth fans are formed where ice sheets reach the continental shelf break, typically as fast flowing ice streams, and deliver large volumes of glaciogenic sediment directly to the upper slope by debris flow processes [*Vorren and Laberg*, 1997; *Vorren et al.*, 1998; *Ó Cofaigh et al.*, 2003].

[22] GZWs on the midshelf and inner shelf comprise localized sediment accumulations, characterized by dipping subbottom reflectors truncated by a gently dipping reflector and overlain by acoustically transparent sediment (Figure 7). Such GZWs are formed by the deposition of unconsolidated, saturated till that is transported subglacially by an ice stream and deposited at the grounding line [cf. *Alley et al.*, 1989]. Top set beds are a product of direct deposition as basal till at the ice stream base, while foreset beds are formed by release of till at the grounding line and subsequent remobilization of this sediment by debris flow processes. GZWs can be formed during either ice sheet advance, ice sheet retreat or during a readvance of the ice margin. Swath bathymetric records of GZWs in inner Belgica Trough show that MSGL are incised into the surface of the wedges but do not continue across them; that is the fronts of the GZWs (transverse sediment scarps) interrupt the MSGL (Figure 4a). This indicates that the episodes of grounding zone stabilization did not occur during ice sheet advance because, in that case, the MSGL would be continuous across the scarps that mark

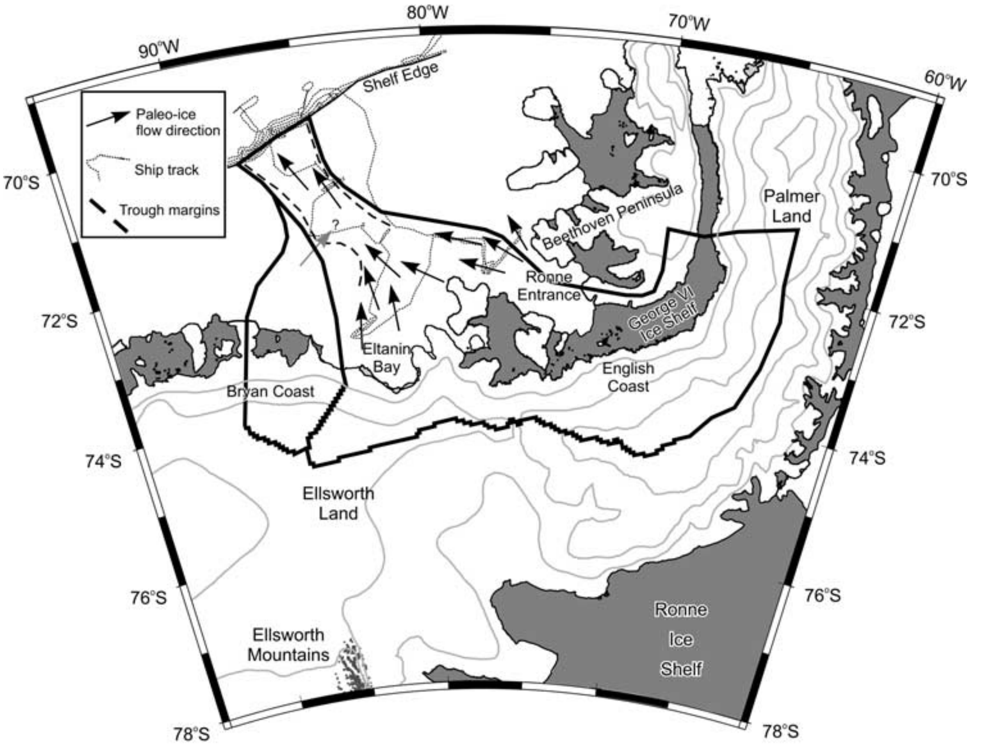

Figure 9. Paleoice flow directions in the study area mapped from the orientation of streamlined subglacial bed forms. Note bifurcation of flow emanating from the Ronne Entrance and convergence of flow into the head of Belgica Trough. Area enclosed by solid line represents the interpreted extent of the Belgica Trough drainage basin assuming that the main ice divide during times of glacial maximum was in the same position as today. The area to the west also enclosed by a solid line is a possible additional part of the drainage basin. Much of the ice sheet bed in Ellsworth Land is near or below sea level, and the ice divide in this area may have been in a different position at glacial maximum. Map projection is polar stereographic.

the former grounding line, whereas the scarps interrupt the MSGL. This implies that the GZWs formed during either ice sheet retreat or during readvances of the ice margin. Such readvances are most likely to have occurred during regional deglaciation, hence the timing of GZW formation would have been broadly similar in both cases. Iceberg scours occur in the outer part of Belgica Trough in water depths of greater than 600 m (Figure 5a). The depth of these scours within the trough suggests that they are associated with ploughing by large icebergs calved from the retreating ice sheet margin during regional deglaciation.

[23] The location of ice streams is commonly associated with areas of soft substrate, either in the form of unconsolidated sediments, or soft and easily erodible bedrock [*Anandakrishnan et al.*, 1998; *Studinger et al.*, 2001]. Streaming over these soft beds is either by subglacial sediment deformation or basal sliding, or some combination of these processes [*Alley et al.*, 1986; *Engelhardt and Kamb*, 1998; *Kamb*, 2001]. It has also been suggested, based primarily on investigations of paleoice streams, that streaming can occur over areas of hard bed composed of crystalline bedrock [*Evans*, 1996; *Ó Cofaigh et al.*, 2002; *Stokes and Clark*, 2003]. In some localities on the Antarctic continental shelf, a transition from streamlined crystalline bedrock to drumlins, and then to MSGL in soft sediments has been observed [*Shipp et al.*, 1999; *Wellner et al.*, 2001]. This geomorphological transition has been inferred to represent a downflow change from slow ice sheet flow over the crystalline bedrock, to a zone of flow acceleration recorded by the drumlins (representing the onset zone of an ice stream), to the high velocities of the main ice stream trunk as recorded by the MSGL [*Wellner et al.*, 2001].

[24] On the basis of their rough and irregular appearance on the swath records, and the apparent absence of sediment on TOPAS records, the crudely streamlined forms in inner Eltanin Bay appear to be formed largely in bedrock. North of about 72°35′S and west of 81°W these crudely streamlined forms evolve into drumlins and then MSGL. The MSGL in Belgica Trough are formed in an acoustically transparent sediment unit that is interpreted as a till. Assuming the most elongate bed forms record the highest flow velocities [cf. *Clark*, 1993; *Stokes and Clark*, 1999, 2002; *Ó Cofaigh et al.*, 2002], MSGL record streaming flow through Belgica Trough toward the shelf edge. Thus the highest inferred flow velocities occurred over the area of soft bed. Shorter bed forms in Eltanin Bay that exhibit a convergent orientation are predominantly formed in bedrock.

[25] We propose that the zone of crudely streamlined bedrock and drumlins in Eltanin Bay represents the onset zone of a paleoice stream in Belgica Trough. Streaming

would be enhanced by the presence of a topographic trough, which would facilitate strain heating and an increase in velocity [cf. *Iken et al.*, 1993]. However, the relationship of the MSGL to the area of the trough underlain by a soft bed implies that subglacial geology also acted as a major control on the development of streaming flow.

4.2. Paleoglaciology of the West Antarctic Ice Sheet on the Bellingshausen Sea Margin at the LGM

[26] The streamlined subglacial bed forms imaged by swath bathymetry in Belgica Trough, Eltanin Bay and the Ronne Entrance record flow of a grounded ice stream toward the edge of the continental shelf. Flow directions mapped from the orientation of the bed forms show that ice flow into the head of Belgica Trough was the result of convergence of ice emanating from Eltanin Bay and the Ronne Entrance (Figure 9). This coalescent ice mass then flowed along the trough, and reached at least as far north as 70°37′S on the outermost shelf. Belgica Trough was thus the pathway for a major ice sheet outlet that was fed by ice draining from the southern part of the Antarctic Peninsula Ice Sheet through the Ronne Entrance, as well as ice from the WAIS draining through Eltanin Bay. These ice masses coalesced in Belgica Trough and extended to the outermost continental shelf and probably the shelf edge (Figure 9). The presence of an additional outlet that flowed northward out of the Ronne Entrance, is implied by the NNW orientated MSGL and drumlins immediately west of Beethoven Peninsula (Figures 1 and 2).

[27] The subglacial bed forms that we document record the most recent episode of ice stream advance through Belgica Trough to the continental shelf edge. We estimate the area of the drainage basin that fed this ice stream by assuming that the main ice divides in West Antarctica and Palmer Land at times of glacial maximum were in the same positions as today. We inferred the positions of the lateral boundaries of the drainage basin on the basis of topographic data and paleoice flow directions interpreted from the multibeam data. By this method we conclude that the basin probably encompassed southwestern Palmer Land and parts of southern Alexander Island and the Bryan Coast of Ellsworth Land (Figure 9). An additional part of the Bryan Coast farther west may also have contributed ice to the Belgica Trough, but we only observe bed forms that suggest flow from this region in one small area. During periods when the Belgica Trough paleoice stream reached the continental shelf edge, the total area of the drainage basin feeding this outlet would have been about 217,000 km^2 if it did not include the western part of the Bryan Coast, and about 256,000 km^2 if it did include that region.

[28] Bedrock topography in central Palmer Land rises 1500–2000 m above sea level and has an important effect in concentrating precipitation [*Turner et al.*, 2002]. Therefore we consider it unlikely that the main ice divide was displaced from central Palmer Land at times of glacial maximum. However, between 73°W and the Ellsworth Mountains (Figure 9), bedrock topography is generally of low elevation and three-dimensional models of the glacial maximum WAIS show the main divide in Ellsworth Land offset to the south of its present position [e.g., *Stuiver et al.*, 1981; *Huybrechts et al.*, 2002]. Our estimate of 217,000–256,000 km^2 for the area of the drainage basin feeding the Belgica Trough ice stream compares with areas of 48,000–570,000 km^2 for modern drainage basins within the WAIS, and a total area of grounded ice in the modern WAIS of about 2,000,000 km^2 [*Vaughan et al.*, 1999]. The only two modern drainage basins within the WAIS that exceed 300,000 km^2 in area (Siple Coast and Pine Island-Thwaites) are composite basins with more than one outlet.

[29] The present net surface mass balance in the parts of Palmer Land and Ellsworth Land that we interpret as having been within the Belgica Trough drainage basin is >500 kg m^{-2} yr^{-1}, which is more than three times the Antarctic average of 149 kg m^{-2} yr^{-1} [*Vaughan et al.*, 1999; *Turner et al.*, 2002]. If net surface mass balance was also higher than average in this area during glacial periods, then the outflow from the basin would have been disproportionately large compared to its area. Therefore the Belgica Trough probably represents one of the main outlets of the WAIS during late Quaternary glacial periods.

[30] Glacial trim lines on the northern part of the eastern flank of the Ellsworth Mountains (Figure 9) indicate a former ice surface elevation up to 1900 m above present, ignoring isostatic compensation [*Denton et al.*, 1992]. This observation is consistent with the hypothesis that a major ice divide was close to the northern end of the range during glacial periods. However, the age of the trim lines remains unknown, so it is not clear whether or not they represent the LGM ice surface, and it is even possible that they formed in pre-Quaternary times [*Denton et al.*, 1992].

[31] Although there is some crosscutting of bed forms in the outer shelf trough (Figure 4b), this is localized in occurrence and relatively minor. The trajectory of former ice flow through the trough was consistently toward the shelf edge (Figure 9). MSGL are formed in the upper part of a subglacial till unit, and in core section this till is overlain directly by deglacial and postglacial sediments (Figure 6). These sediments are typically $\leq$0.5 m in thickness. The streamlined subglacial bed forms that we image on the floor of Belgica Trough formed during the most recent episode of ice advance to the shelf edge. In conjunction with the thin sequence of deglacial and postglacial sediments that overlie the till associated with this advance, the simplest interpretation is that the timing of ice sheet advance occurred during the last glaciation and that grounded ice therefore reached the shelf edge at the LGM.

[32] The new data presented in this paper fill a major gap in reconstructions of the Antarctic Ice Sheet during the last glacial cycle [cf. *Bentley and Anderson*, 1998; *Bentley*, 1999]. They indicate an extensive WAIS at the LGM on the Bellingshausen Sea continental margin, which advanced to the continental shelf edge. In conjunction with data from further to the west in Pine Island Bay [*Lowe and Anderson*, 2002; *Dowdeswell et al.*, 2005; J. Evans et al., Extent and dynamics of the West Antarctic Ice Sheet on the outer continental shelf of Pine Island Bay, Amundsen Sea, during the last glaciation, submitted to *Marine Geology*, 2005] and northeast around the Antarctic Peninsula [*Pudsey et al.*, 1994; *Ó Cofaigh et al.*, 2002, 2005; *Evans et al.*, 2004, 2005] this implies an extensive ice sheet configuration during the LGM along the Antarctic Peninsula, Bellingshausen Sea, and Amundsen Sea margins, characterized by fast flowing ice streams which drained extensive basins of

the WAIS and Antarctic Peninsula Ice Sheet through cross-shelf bathymetric troughs, and reached the outermost shelf or shelf edge.

5. Conclusions

[33] 1. Geophysical data show that during the last glacial cycle Belgica Trough supported a major, grounded outlet of an expanded WAIS that drained to the continental shelf edge as a fast flowing ice stream. The drainage basin feeding this outlet encompassed parts of southern Alexander Island, southwestern Palmer Land and the Bryan Coast of Ellsworth Land. Its total area would have exceeded 200,000 km^2.

[34] 2. Streamlined bedrock and drumlins mapped by swath bathymetry show that this ice stream was fed by convergent ice flow from Eltainin Bay and bays immediately to the east, as well as by ice flow draining the southern part of the Antarctic Peninsula Ice Sheet through the Ronne Entrance.

[35] 3. The former presence of an ice stream in Belgica Trough is recorded by MSGL formed in soft till and a major trough mouth fan on the continental margin in front of the trough. TOPAS subbottom profiler data reveal that the surface of this fan is composed of debris flow deposits.

[36] 4. The relationship of MSGL to the area of Belgica Trough underlain by a soft bed implies that subglacial geology acted a major control on streaming flow in Belgica Trough and probably augmented the topographic control imposed by the trough. Grounding zone wedges within Belgica Trough record stillstands of the ice sheet margin during deglaciation and imply a staggered pattern of retreat.

[37] 5. These new data indicate an extensive WAIS at the LGM on the Bellingshausen Sea margin, which advanced to the continental shelf edge. In conjunction with paleoglaciological reconstructions from further to the south and north, this implies that ice sheet configuration during the LGM along the Antarctic Peninsula, Bellingshausen Sea and Amundsen Sea margins was regionally extensive. Fast flowing ice streams drained the WAIS and Antarctic Peninsula Ice Sheet through cross-shelf bathymetric troughs and reached the outermost shelf and shelf edge.

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